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INTEGRATED PRODUCT AND PROCESS MODELS: TOWARDS AN INTEGRATED FRAMEWORK AND REVIEW

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Abstract

While product models and process models have a long standing transiting, there are few models that integrate the two type of models. Those that exist are research systems, which even if validated in industry do not have a broad uptake to date. This paper develops an integrated framework for product and process models based on the purpose the models are put it building on a model of Browning and Ramasesh. Selected integrated model are classified according to the framework. This revealed the no model to date gives equal weight to product and process models.

Keywords: product modelling, Process modelling, Integrated product development

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1 MOTIVATION

Technical innovation and a desire for individualization have led to an increasing variety of products, requiring a balance between the development of new solutions and the adaptations of existing ones, which at the heart of which is a trade-off between process time and product capability. Many current products require a close integration between hardware, software and conditions of use. At the same time regulation and customer demand have required product development processes to become shorter. To reduce the risk associated with these products designers need to consider the product and its development process together to find the best compromise between innovation and product development efficiency. To make these potential trade-offs explicit and discuss them across an organisation, we propose that companies would greatly benefit from integrated product and process models. Such models incorporate both the product view and the process view to make the complex interactions between an emerging product and the organisation that creates it more understandable and more traceable for decision makers. At the moment products and processes are largely modelled in separate tools and modelling approaches, so that these trade-offs have to be made in the minds of experienced engineers and can't be shared and discussed easily across teams.

This paper aims to contribute to this developing area by reviewing current state-of-the-art in integrated product-process models, i.e. models where the link between products and process models is an explicit part of the modelling approach. The paper is the result of collaboration between members of the MMEP special interest group to provide an introductory literature review for researchers in the area and to develop a categorization framework to relate the different models. The group selected the process model framework of Browning and Ramasesh (2007) as a starting point and extended it to include the product domain. The combined framework was refined in a workshop and three remote meetings. The framework highlights two types of integrated models: (1) those generated specifically as integrated models, and (2) those which are used as integrated models, but had originally been developed as either product or process models. It also draws attention to under-researched areas that deserve further attention.

A brief overview of product models and process models is provided in Section 2. Established modelling approaches that integrate product and process domains are discussed in Section 3. The categorization framework for integrated modelling is introduced in Section 4 and discussed in Section 5. Conclusions are drawn in Section 6, together with suggested topics for future research.

2 PRODUCT MODELS AND PROCESS MODELS

Models are by their very nature an abstraction of reality (Frigg, 2003) that is generated for a specific purpose. Their utility might deteriorate over time, for example if the process changes but a model of it is not updated. While there are modelling conventions, every modelling activity involves an element of subjective selection of which aspects to include in the model. Models can be seen as “an excerpt of reality” (Stachowiak, 1973) or as expressions of intention for reality. Models draw attention to one aspect of the target potentially at the expense of others. George P. Box famously said: “all models are wrong, but some are useful” (Box and Draper, 1987).

The majority of product and process models in engineering design have been developed over many years for the specific needs of one of these two domains. Some models bridge both domains. Covering the models exhaustively far exceeds the scope of this paper - therefore this section provides an overview of the different types of model.

2.1 Product modelling

Designers and engineers rarely interact with the product or a prototype directly. Instead, they create, develop, improve and assess different types of product models. While they may discuss a product verbally, communication is mainly facilitated through product models. Product models as a means of abstract representation and visualisation of information are not limited to mathematical or computational models used in for example finite element analysis or control system design, which typically occur in a later phase of the design process. Graphical product models like sketches, diagrams, CAD models, and technical drawings as well as bills of material are arguably of much higher importance for designers (Andreasen, 1994).

Different information about the product under development requires different models for representing that information appropriately. Different modelling approaches and multiple models are used during the design process by different stakeholders (Eisenbart et al. 2011). Examples include models for requirements, function models, geometry and material (CAD), models of the final result of product development (e.g. bill of material, technical drawings, manufacturing information) and general models used for representing a multitude of different information (e.g. DSM (Eppinger et al., 1994) and MDM (Lindemann et al., 2009)), modelling languages such SysML, and simulation models. These models can potentially be integrated with each other and with process models, unlike sketches, verbal descriptions, and physical models, which can only be referred to.

The predominant types of product models used in practice are arguably CAD/CAM models. The structure of a CAD model consists of components (assembly- and individual parts) as well as of a number of form elements, which are combined and adapted during the constructive process. One challenge associated with geometrical modelling is linking to non-geometrical information such as functional or product descriptions, which form interfaces to other aspects of the product. A comprehensive product model includes product master data, product structure, documents and their structures. A product's structure, which is often represented in bills of materials (BOM) describes all the parts, systems, assemblies, individual components and materials. It can take different forms throughout the product lifecycle, depending on the application of the model (Albers et al., 2014). Technical drawings are graphical representations of parts, which contain information such as dimensioning, deviations, tolerances, tolerance ranges, material, surface finish as well as required manufacturing and test methods. Products are increasingly being seen as systems or part of systems, so that Systems Engineering is increasingly playing an important role in the early phases of design processes. Modelling languages such as SysML can model requirements, system behavior and system structures that can be interlinked and visualized (Haskins et al., 2011). Multidisciplinary consideration of systems led to the development of metamodels created by Model Based Systems Engineering (MBSE) that contain not only the information usually incorporated in BOMs, but also interactions between the content of individual information items.

2.2 Process modelling

Hammer (2001) stated that: *“A process is an organized group of related tasks that work together to create a result of value”*. Product development process management is concerned with planning, monitoring, and controlling of tasks using theories, method and models (Wynn, 2007). The objective is to explain, manage and/or improve the design and development process.

Process models are idealised abstractions of reality. They are generally more ambiguous than the product models discussed above and can depict different ideas about the process, for example the ‘current process’ or ‘to be process’, at different levels of granularity. A process model can describe multiple processes if it is made at a suitably high level of abstraction. At a lower level, details of activities are also often similar. However companies are often interested in a middle ground, namely models specific to their products and processes which also allow them to gain an overview and reason about the process.

Modelling frameworks or methods are used to build process models. Frameworks can be considered as ‘virtual sandboxes’ and models as ‘sandcastles’ (O’Donovan et al., 2005). Frameworks include the ‘raw material’, ‘tools’, and techniques to build models. Their properties, like the properties of different materials, limit the characteristics of models that might be built. The insights drawn from building process models can provide the basis for process improvement (Fricke et al., 1998). Different types of design process model are discussed in the following paragraphs.

Abstract models present a generic view on design processes. They are high-level in nature and often emphasise aspects of creativity in design. Procedural models are prescriptive or descriptive models that express insights into the nature of product development and design processes. Examples are Pahl et al. (1996) prescribing a design process, or Hales and Gooch (2004) depicting a traditional product development process. Due to their generality they might not be suitable to help daily managerial decisions during planning and execution of a project. Support for these activities can be provided by analytical approaches focusing on specific instances of the design process (Wynn, 2007). They are comprised by a modelling framework that describes the process; and techniques, tools or methods to investigate and support improvements. Wynn (2007) classified them into System Dynamics models,

Agent Based models, Queuing models, and Task network models. The categories are described below; in practice, many approaches discussed in the literature are hybridisations of these categories.

System Dynamics (SD) models consider projects as work-processing systems that can be decomposed into stocks of tasks, where tasks flow between the stocks according to rates that are governed by a network of interacting influences. In order to study the dynamic behaviour of the process, a number of factors will influence on the work or information flows. Cooper (1993) uses a SD model to study rework in design process. Queuing models are concerned with utilisation of limited resources in a project. Traditionally, they simulate projects as a set of working stations that process and output information to the next station. Such projects usually have well understood links and steady processes such as manufacturing systems or supply chains. Thus queuing models are well suited for homogeneous activities due to the repetitive nature of workflows. In design, stochastic queuing models include the work of Adler et al. (1995) and Golenko-Ginzburg et al. (2003). Agent-based models comprise a distinctive type of stochastic design process model. The models consist of a set of entities (agents) characterised by their attributes, that interact with each other following defined rules in a given environment (Barbati et al., 2012). Agents behave as individual information-processing elements with rational responses to the limited input of information they receive. In the context of design process, agent based models mainly focus on communication, collaboration, and negotiation of decisions between design process stakeholders. For instance, the Virtual Design Team (VDT) framework assesses different configurations of design processes using discrete-event simulation. VDT models the organisation and its interactions with the work plan to simulate information processing, communication and coordination behaviour between designers (Cohen, 1992). More recently Crowder et al. (2012) developed Integrated Product Teams (IPT), a collaborative model to simulate teamwork. Task network models present a process as a set of information processing activities that must be completed in order to reach the desired objectives (Browning and Ramasesh, 2007). A number of significant modelling frameworks can be found within this category. IDEF0 is a method used to represent interconnected functions and the associated information exchange in a system or enterprise (NIST, 1993). CPM, and its extensions PERT and GERT, are techniques to analyse the minimum and maximum process duration as well as the scheduling flexibility for a task (PMI 2013). Some frameworks interlink process modelling with elements that represent the product they aim to design. For instance, the integrated Product Engineering Model (iPeM) is a framework (Albers and Braun, 2011) that interlinks process activities with product elements within the system of objects. IDEF3 is a precedence model aiming to capture knowledge about process flow and object states transitions. Flowchart-oriented methods such as Petri nets (Peterson, J. L., 1982) and ASM (Wynn et al, 2006) combine diagrammatic graphical depiction of a process with the use of parameters or tokens to drive the design process. Such elements can represent a range of design components or states necessary for an activity to be executed. Signposting (Clarkson PJ and Hamilton JR, 2000) and APDP (Adaptive PD process) (Levardy and Browning, 2009) moved away from conventional prescriptive process definitions in which a set of activities is defined, sequenced and scheduled to reach the project's desired result. The rationale is that during a design process, the actual path is built upon the outcome of currently performed activities. Therefore these authors model processes through a set of activities without dependencies that would combine dynamically by adapting to the current state of the design to form the process path. In APDP and in later versions of Signposting, the process is simulated to find the path that yields in the highest performance value in terms of risk reduction accounting for technical performance, cost, and time to complete. Finally, DSM is a modelling framework consisting of a square matrix with identical row and column labels. DSM is used to capture and represent dependencies between elements represented by these labels (see Browning 2001 for a review). Static DSMs have been use to represent the interaction between system elements that exist simultaneously, for instance in product architectures or organizations. Time-based DSMs are characterised such that the ordering of the rows and columns indicates a directional flow through time, and are often used to model design processes.

3 CATEGORIZATION FRAMEWORK FOR INTEGRATED PRODUCT- AND PROCESS-MODELS

The relevance of integrated product- and process-models is rising due to product development performance targets such as time, cost and quality which relate to both the product- and the process-

domain and due to increasing information flow between various business functions and different engineering disciplines throughout the PD process. However, except for Heisig et al. (2014) who examined the information elements in 15 integrated models for knowledge capture and management, no comprehensive overview exists on integrated models to the authors' knowledge. This paper addresses this research gap by deriving a categorisation framework for integrated product- and process-models. As illustrated in Table 1 knowledge management corresponds to sub-categories of the proposed framework and thus, the scope of this framework is broader than that developed in Heisig et al.'s article.

To derive the categorisation framework the design literature was first searched for existing categorisation frameworks for product and process models. While no well-established categorisation framework was found for product models, several well-established categorisations of process models do exist (Smith and Morrow, 1999; Wynn and Clarkson, 2005; Browning and Ramasesh, 2007). Due to its practically oriented structure along managerial purposes of modelling, the framework of Browning and Ramasesh (2007) was selected as a starting point to develop a categorisation framework for integrated models.

Browning and Ramasesh's original framework comprises four major categories with multiple sub-categories (see left-hand side of Table 1). First, process models used for project visualisation illustrate interactions and commitments, provide a common mental model to the workforce and generate views which underline the most relevant information for certain user groups. Second, process models used for project planning assist in determining necessary activities, in finding efficient process structures, in estimating and improving key process performance metrics and in allocating resources. Third, process models used for project execution and control inform on the progress made and the best direction to go, and also support dynamic re-planning of projects. Fourth, process models used for project development capture how design is executed and how it might be executed, thus supporting continuous improvement.

To extend this categorisation framework to integrated product and process models, the authors systematically explored the applicability of the categorisation to the product domain by identifying analogous sub-categories (i.e. looking for different purposes under the same category) for product modelling, dropping non-applicable process modelling sub-categories, and adding additional product modelling sub-categories. This resulted in the following categorisation of purposes for product models (see right-hand side of Table 1):

1. **Product visualisation:** including the visualisation of components, their interfaces, constraints and requirements as well as the generation of views which underline the most relevant product information for specific user groups. This functionality is offered by CAD models or product rendering.
2. **Product synthesis:** including the specification and negotiation of requirements as well as the systematic planning of product functions, behaviours and structures. SysML models could be used for this, as well as some aspects of CAD modelling.
3. **Product analysis and evaluation:** including evaluating the designed product's adherence to specifications as well as its usability and usefulness. Finite elements analysis models for example fall into this category.
4. **Product Lifecycle Support:** including support of the design project through documentation and knowledge transfer, concrete decision support, e.g., for engineering change management, and support of other business functions, e.g., manufacturing or logistics. For example bills of material fall into this category.

Table 1 shows the categorisation framework for product and process models, which combines the original framework by Browning and Ramasesh (2007) and the extensions described above. The framework is limited to engineering design product and process models, and is not intended to categorise general systems engineering modelling approaches like SysML that can be applied to any system. The models are grouped by their main purpose and the elements that the models contain.

Integrated product and process-models were then categorised using the framework, by associating the models with their modelling purpose where one model can have multiple purposes. This is important because often models are used for different purposes than originally intended (Eckert and Clarkson, 2010). For example, the APDP model by Lévardy and Browning (2009) supports project planning, execution and control by finding activity schedules that adapt to a project's risk profile. Moreover, because the model considers not only schedule and cost but also technical performance risks it can be

also used to analyse and evaluate the maturity of an evolving design. The categorisation of some established integrated models is demonstrated in the following section.

Table 1: Categorisation framework for integrated product- and process-models based on Browning and Ramasesh (2007) as shown in the left column

Original framework for process models	Extension for product-modelling purposes
Project visualisation <ul style="list-style-type: none"> • Actions, interactions and commitments • Customised views 	Product visualisation <ul style="list-style-type: none"> • Components, interfaces, constraints, requirements • Customised views
Project planning <ul style="list-style-type: none"> • Making commitments • Choosing activities • Structuring the process 	Product synthesis <ul style="list-style-type: none"> • Specification and negotiation of requirements • Product functions, behaviours and structures
Project execution and control <ul style="list-style-type: none"> • Monitoring commitments • Assessing progress • Re-directing • Re-planning 	Product analysis and evaluation <ul style="list-style-type: none"> • Verifying against specifications, i.e. evaluating the product, including maturity • Validating against user needs, i.e. evaluating the product use
Project development <ul style="list-style-type: none"> • Continuous improvement • Organization learning and knowledge management • Training • Compliance 	Project and business support <ul style="list-style-type: none"> • Documentation and knowledge management • Decision support • Support of business functions

4 CLASSIFYING EXISTING INTEGRATED PRODUCT- AND PROCESS-MODELS IN THE FRAMEWORK

This section briefly reviews modelling approaches that integrate the product and process domain and categorises them in the framework discussed in section 3. The aim is not to provide an extensive discussion of existing integrated models, as this would go beyond the scope of this article. Instead Table 2 lists integrated product and process models with a representative reference and a short summary, and indicates how they can be characterised according to their purpose in the product and process domain. The authors drew on existing literature reviews of product and process models to select those that cover both domains. This sample is not representative or exhaustive but rather serves to demonstrate the application of the proposed framework. The bottom three models in Table 2 are also included in the review of Heisig et al. (2014) and, while concentrating on knowledge management, also cover other domains in the presented framework. It is worth noting that the other models reviewed in Heisig's article can also be categorised in this framework with a focus on project development and support. In the presented framework, dedicated product or process models would only have entries in their respective domain, while integrated models have entries on both sides. Several of the models considered in this section could be used for a range of purposes in both domains.

In order to provide a clearer picture of the model purpose we indicate primary model purposes with “●” and secondary purposes with “○”. These purposes were assigned to the models in Table 2 during a workshop with 7 academic researchers who work in the area of product and process modelling. The primary purpose indicates that the model was specifically developed for this purpose and is used accordingly. The secondary purpose indicates that the model was not specifically developed for the purpose but can be used for it or is used for it in practice.

Table 2. Classification of existing models in the framework

Name / Reference	Summary	Process				Product			
		Visualisation	Planning	Execution&Control	Development	Visualisation	Synthesis	Analysis&Evaluation	Support
DMM/MDM Danilovic and Browning (2007)	Models dependencies between elements within and across different domains, thus capturing whole systems.	●	●			○		○	○
DeSim Gärtner et al. (2009)	Supports project and change management by accounting for cross-domain dependencies to simulate probabilistic project duration and cost.		●	●					●
ISF Ahmad et al. (2013)	Identifies change propagation linkages and creates dynamic checklists to assess change impacts on product and redesign process.		●	●			○	○	●
CPiW Wynn et al. (2014)	Simulates change propagation through design workflows, predicting resource requirements and schedule risk.		●	●					●
Chua and Hossain (2012)	Predicts change propagation on downstream activities due to change initiated at various stages; assesses impact on design completion and redesign.		●	●					●
Signposting Clarkson and Hamilton (2000)	Guides task selection throughout the design process based on designers' confidence in the design as described by various parameters.		●	●				○	
APDP Lévardy and Browning (2009)	Simulates a set of possible activities and rules for self-organisation to support adaptive management throughout the design process.		●	●				○	
ASM Wynn et al. (2006)	Models task precedencies and dependencies based on their interaction with design parameters; represents multiple task hierarchies and dynamic behaviour.		●	●				○	
DEPNET e.g. Ouertani et al. (2007)	Identifies deliverables and tasks requiring rework due to changes caused by design conflicts; investigates task overlapping and multifunctional interaction.	●		○		●			●
IDEF3 Mayer et al. (1995)	Captures different user perspectives on precedence and causality relationships in a process and can integrate product information.		●		●	○			
FBS-PPRE Bernard et al. (2006)	Evaluates enterprise performance by extending the function, behaviour and structure views towards processes, products and resources.				●		○	○	●
Pro2Kon Abramovici and Chasiotis (2002)	Captures process-, design-oriented product-, behaviour-oriented product- and configuration knowledge.				●	○	○	○	●
CoMoDe Gonnet et al. (2007)	Captures and represents design process on two levels of granularity (incl. process and product information)			●	●				●

For instance, while DSMs can model the dependency structure between the components of a product or the tasks in a process, DMMs (Domain Mapping Matrix) explicitly map dependencies between elements of different domain (e.g. product and process, although many others are possible). DSMs and

DMMs can be combined in a MDM (Multiple-Domain Matrix) to represent a system's structure across multiple domains. This allows direct integration of models of the product and process domain by modelling the dependencies between the elements within and across the two domains. MDMs (see, e.g. Danilovic and Browning (2007)) can be applied for project and product visualisation, for project development or for design support. However, if the major purpose of MDMs is to represent and study the structure of the design process, from this perspective it would be categorised under project planning.

The other models in Table 2 are categorised in a similar manner, indicating their purposes in both domains. Arguably, a straightforward differentiation between primary and secondary purposes might not always be possible or at least remain debatable. However, we believe that this distinction is an important one as it captures both the original objective and the capabilities of the models. Due to the limited scope of this conference paper we do not discuss the categorised models in Table 2 in more detail and point the interested reader towards the original articles.

5 DISCUSSION OF KEY CHARACTERISTICS OF CATEGORIZATION FRAMEWORK AND CRITICISM

Industry is asking for integrated models which allow them to carry out all engineering activities in an integrated fashion pulling information seamlessly across a heterogeneous set of models. Table 2 suggests very clearly that the reality of modelling is far from this. All the integrated models that have been identified in the literature are predominantly process models that link tasks or activities to product related information. For example IDEF0 models link tasks to their input and output, which can be product descriptions, while ASM can be used to describes the advance in parameter maturity associated with tasks. None of the models cover all different aspects identified by the framework. The largest number of entries in the product models column is for product models generated to support the project. These are typically product representations that would not be used normally as part of a product development process. For example designers don't have models of the maturity of key parameters required for the applied signposting model, rather they have to generate them as part of thinking through the process.

The uptake in industry of these integrated modelling frameworks to date is limited. IDEF has been around since the 1980s and is used in industry, however rarely implemented as completely as intended by the original creators of the method. The research systems have been validated to various extents ranging from theoretical discussions, through simplified demonstrative case studies, to industrial deployments. However, the wider industrial uptake is limited. Some approaches have been rolled out through the industrial collaborations of the chairs and/or teaching.

None of the integrated models that were reviewed map process to standard product representations such as CAD models or BOMs that were discussed earlier in the paper. This might be indicative of a fundamental underlying problem of different fundamental structure of the models that need to be integrated. For example an assembly BOM groups components by the assembly activities that need to be carried out to put the product together. Some systems arrive preassembled from the suppliers, while others are put together during the assembly process and therefore are entered explicitly in the BOM, so that engines and rivets are shown on the same level of detail in the BOM. However the tasks associated the designing or validating are completely different. While the rivets in this example are likely to be carry over parts with no tasks associated with them, the engine might have several large tasks associated with its specification and validation, if provided by a supplier, or many more tasks, if designed in-house. Components and systems are often grouped in activities, for example for testing purposes and therefore there has to be a many-to-many relationship between tasks and components. For both products and processes one of the challenges is to find suitable breakdowns at different levels of detail, which allow composition and decomposition of elements, as many sub-tasks or components could be part of several tasks or systems. Companies in practice work round this through practical modelling conventions, for example by assigning components to systems by the team structure in which they are designed; and individuals keep track of additional links.

As well as integrated models, integrated frameworks exist which bring different types of design information together into one coherent construct, such as in the work of Buur and Andreasen (1989) and in the iPeM framework. The iPeM, for example, defines ten generic activities of a product development process e.g. planning the project, identifying the market opportunities and requirements

and evaluation of the product in service. These activities are associated with the set of objectives or requirements and the resulting product description. More detailed product and process descriptions can be associated with each step.

This raises the question to which extent it is possible to integrate all aspects of product and process modelling. A similar discussion exists around cyber-physical systems, which aim to model artificial and human systems together bridging the divide between many different fields. One challenge is to assure that integrated models are sufficiently complete and do not have important gaps that fall between the competencies of the different people involved.

6 CONCLUSION

While many modelling approaches exist for products and processes, very few address the integration of both. Those that exist only link aspects of product and processes. Most of the existing process models are research systems, which even if validated in industry do not have a broad uptake to date.

To date, no integrated product and process model exists that gives equal weight to product modelling as to process modelling and furthermore that no models covers all aspects highlighted in the framework. However, the question is not how to integrate models to cover all conceivable issues, but rather how to bring them together in a way that allows decision makers to gain useful overview and reason about the connection between products and processes.

This paper is just a starting point for a broader review and evaluation of integrated product and process models. The authors are planning to extend this study to analysing which aspects of product and process modelling can be usefully combined.

REFERENCES

- Abramovici, M., Chasiotis, C. (2002) Integrated Documentation of Procedural Knowledge in Product Development, Proceedings of Integrated Product and Process Development, Wroclaw, Poland.
- Ahmad, N., Wynn, D.C., Clarkson, P. J. (2013) Change Impact on a Product and its Redesign Process: A Tool for Knowledge Capture and Reuse. *Research in Engineering Design*, 24(3) pp. 219-244.
- Adler, P.S., Mandelbaum, A., Nguyen, V., Schwerer, E. (1995) From Project to Process Management: An Empirically-Based Framework for Analyzing Product Development Time, *Management Science* 41, pp 458-484.
- Albers, A., Braun, A. (2011) A generalized framework to compass and to support complex product engineering processes, *International Journal of Product Development* 25(1-3), pp 6-25.
- Albers, A., Lüdcke, R., Bursac, N., Reiß, N. (2014) Connecting Knowledge-Management-Systems to improve a Continuous Flow of Knowledge in Engineering Design Processes, *Proceedings of TMCE 2014*, pp 393-402.
- Andreasen, M.M. (1994) Modelling – the Language of the Designer, *Journal of Engineering Design*, Vol. 5. Vol.5, pp. 103-115.
- Barbati, M., Bruno, G., Genovese, A. (2012) Applications of agent-based models for optimization problems: A literature review, *Expert Systems with Applications* 39, 6020-6028.
- Bernard, A., Labrousse, M., Perry, N. (2006) LC universal model for the enterprise information system structure, In *Innovation in life cycle engineering and sustainable development*, Springer: Netherlands. pp 429-446.
- Box, G. E. P., Draper, N. R. (1987) *Empirical Model Building and Response Surfaces*, John Wiley & Sons, New York, NY.
- Browning, T.R. (2001) Applying the design structure matrix to system decomposition and integration problems: a review and new directions, *IEEE Transactions on Engineering Management*, 48, pp 292-306.
- Browning, T.R., Ramasesh, R.V. (2007) A Survey of Activity Network-Based Process Models for Managing Product Development Projects. *Production and operations management* 16, pp 217-240.
- Chua, D.K.H., Hossain, M.A. () Predicting Change Propagation and Impact on Design Schedule Due to External Changes. *IEEE Transactions on Engineering Management*, 59(3), pp 483-493.
- Clarkson, P.J., Hamilton, J.R. (2000) "Signposting", a parameter-driven task-based model of the design process, *Research in Engineering Design* 12, pp, 18-38.
- Cohen, G.P. (1993) *The virtual design team: An information-processing model of design team management*, PhD Thesis, Stanford University.
- Cooper, K.G. (1993) The rework cycle. *Project Management in action*, *Project Management Journal*
- Crowder, R.M., Robinson, M.A., Hughes, H.P.N., Sim, Y.W. (2012) The Development of an Agent-Based Modeling Framework for Simulating Engineering Team Work, *IEEE Transactions on Systems, Manufacturing, and Cybernetics - Part A: Systems and Humans* 42, 1425-1439.

- Danilovic, M., Browning, T.R. (2007) Managing complex product development projects with design structure matrices and domain mapping matrices, *International Journal of Project Management* 25, pp 300–314.
- Eckert, C.M., Clarkson, P.J. (2010) Planning Development Processes for Complex Products, *Engineering Design* 21(3), pp 153–171.
- Eisenbart, B., Gericke, K., Blessing, L. (2011) A framework for comparing design modelling approaches across disciplines, *Proceedings of 18th International Conference on Engineering Design*, pp 344–355.
- Eppinger S.D., Whitney D.E., Smith R.P., Gebala D.A. (1994) A model-based method for organizing tasks in product development, *Research in Engineering Design*, 6(1), pp 1–13.
- Fricke, E., Negele, H., Schrepfer, L., Dick, A., Gebhard, B., Hartlein, N. (1998) Modeling of concurrent engineering processes for integrated systems development, *Digital Avionics Systems Conference. Proceedings 17th DASC*.
- Frigg, R. (2003) Re-representing scientific representation. PhD thesis. Department of Philosophy Logic and Scientific Method, London School of Economics.
- Gärtner, T., Rohleder, N., Schlick, C.M., DeSim – A Simulation Tool for Project and Change Management on the Basis of Design Structure Matrices, 11th International DSM Conference, Greenville, South Carolina, USA.
- Golenko-Ginzburg, D., Gonik, A., Laslo, Z. (2003) Resource constrained scheduling simulation model for alternative stochastic network projects, *Mathematics and Computers in Simulation* 63, pp 105–117.
- Gonnet, S., Henning, G., Leone, H. (2007) A model for capturing and representing the engineering design process, *Expert Systems with Applications*, 33(4), pp 881–902.
- Hammer, M. (2001) Seven insights about processes, Presented at the Strategic Power of Process: From Ensuring Survival to Creating Competitive Advantage, Boston, MA.
- Hales, C., Gooch, S. (2004) *Managing Engineering Design*, Springer.
- Haskins, C., Krueger, M., Forsberg, K., Walden, D., Hamelin, R. D. (2011) *Systems Engineering Handbook V3.2.2. INCOSE*
- Heisig, P., Caldwell, N.H.M., Clarkson, P.J. (2014) Core information categories for engineering design – contrasting empirical studies with a review of integrated models, *Journal of Engineering Design*, 25(1-3), pp 88–124.
- Levardy, V., Browning, T.R. (2009) An Adaptive Process Model to Support Product Development Project Management, *IEEE Transactions on Engineering Management*, 56(4), pp 600–620.
- Lindemann U., Maurer M., Braun T. (2009) *Structural complexity management: an approach for the field of product development*. Berlin: Springer.
- Mayer, R.J., Menzel, C.P., Painter, M.K., Dewitte, P.S., Blinn, T., Perakath, B. (1995) Information integration for concurrent engineering (IICE) IDEF3 process description capture method report (No. KBSI-IICE-90-STR-01-0592-02), Knowledge Based Systems Inc. College Station, TX.
- NIST. (1993) Integration definition for function modeling (IDEF0), Computer Systems Laboratory of the National Institute of Standards and Technology. U.S. Department of Commerce, Federal Information Processing Standards Publication 183.
- O'Donovan, B., Browning, T.R., Eckert, C.M., Clarkson, P.J. (2005) Design planning and modelling. In: Clarkson, P.J., Eckert, C. M. *Design Process Improvement: A Review of Current Practice*, Springer: London, pp 60–87.
- Ouertani, M.Z., Grebici, K., Blanco, E., Rieu, D. (2007) DEPNET : A methodology for identifying and qualifying dependencies between engineering data. In: Krause, F-R. *The Future of Product Development*. Springer: Berlin Heidelberg, pp 319–330.
- Pahl, G., Wallace, K., Blessing, L., Pahl, G. (1996) *Engineering design: a systematic approach*. Springer.
- Peterson, J.L. (1982) *Petri net theory and the modelling of systems*, Prentice-Hall.
- PMI (2013) *A Guide to the Project Management Body of Knowledge: PMBOK Guide*, Newtown Square, PA, USA: Project Management Institute.
- Smith, R.P., Morrow, J.A. (1999) Product development process modelling, *Design Studies*, 20(3), pp 237–261.
- Stachowiak, H. (1973) *Allgemeine Modelltheorie*. Springer, Wien.
- Stachowiak, H. (1994) Modell. In: Seiffert, H., Radnitzky, G. *Handlexikon der Wissenschaftstheorie*, 2nd edition, Deutscher Taschenbuchverlag dtv: Munich, pp 219–222
- Wynn, D.C. (2007) Model-based approaches to support process improvement in complex product development, PhD Thesis, University of Cambridge.
- Wynn, D.C., Clarkson, P.J. (2005) Models of designing. In: Clarkson, P.J., Eckert, C.M. *Design Process Improvement: A Review of Current Practice*, Springer: London, pp 34–59.
- Wynn, D.C., Eckert, C.M., Clarkson, P.J. (2006) Applied signposting: a modelling framework to support design process improvement, *Proceedings of the ASME International Design Engineering Technical Conferences (IDETC/CIE2006)*, Philadelphia, PA, US.
- Wynn, D.C., Caldwell, N.H.M. and Clarkson, P.J. (2014) Predicting Change Propagation in Complex Design Workflows, *Journal of Mechanical Design*, 136(8), 081009.